Test synopsis of:

Proton Tolerance of Advanced SiGe HBTs Fabricated On Different Substrate Materials

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Abstract— **The proton tolerance of SiGe HBTs fabricated on a variety of substrate materials is investigated for the first time. The present SiGe HBT BiCMOS technology represents only the second commercially-available SiGe process to be reported for radiation effects. SiGe HBT *dc* and *ac* performance is compared for devices fabricated on silicon-on-insulator (SOI), low resistivity, and high resistivity silicon substrates, and all are found to be total dose tolerant to multi-Mrad radiation levels. We also compare these radiation results to those previously reported for other commercially-available SiGe technologies.**

I. Introduction

Silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) technology is rapidly making in-roads into commercial digital, analog, RF, microwave, and even millimeter wave terrestrial integrated circuit applications due to its attractive combination of high speed, low noise, high integration level, and low cost. In addition, SiGe HBT's are potentially attractive candidates for space communication systems, due to their inherent robustness to ionizing radiation (typically to multi-Mrad total dose levels). Previous research in SiGe HBT radiation effects has focused on SiGe process technologies from only one source (IBM), and were fabricated only on low-resistivity (8-10 Ωcm) Si substrates [1].

The use of alternative (i.e., higher resistivity) substrate materials in SiGe technology is receiving great attention, because substrate coupling, transmission line losses, and passive performance, can all be dramatically improved over that found in conventional low-resistivity (lossy) Si substrates, paving the way for SiGe-based microwave and mm-wave monolithic system implementations. As operating frequencies rise, the use of high-quality transmission lines and low loss passives becomes increasingly critical to robust circuit and system design. Many studies have shown that the incorporation of high resistivity silicon (HRS) or silicon-on-insulator (SOI) technologies can greatly enhance the performance of these passive elements in Si-based technologies [2]–[4]. It is also anticipated that the use of SiGe HBTs on SOI substrates will greatly reduce the apparent softness of high-speed SiGe technology to single-event upset [5], the only obvious weakness of SiGe technology for space applications. This work reports, for the first time, the proton tolerance of the commercially-available Jazz SiGe-120 SiGe HBT BiCMOS process on standard 8 Ω-cm Si substrates, in conjunction with experimental process variations utilizing a 1500 Ω-cm substrate, and a 2 μm thick SOI substrate. We also compare these radiation results to those previously reported for other commercially-available SiGe technologies.

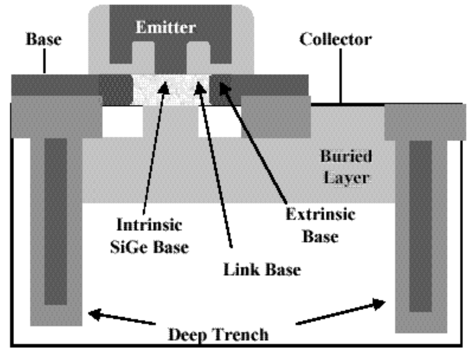

Fig. 1. Schematic device cross-section of the SiGe HBT under investigation.

II. SiGe HBT BiCMOS Technology

The SiGe BiCMOS technology under investigation is a commercially-available SiGe process featuring 6 layers of metalization, both high-speed and high-breakdown SiGe HBTs, 180 nm CMOS devices, high-Q spiral inductors, and high-Q MIM capacitors [6]. The process utilizes shallow and deep trench isolation and a self-aligned emitter-base structure, resulting in low base resistance and reduced capacitive parasitics [6]. A schematic cross-section of this SiGe technology can be seen in Figure 1 [6]. Typical device performance metrics are summarized in Table I [6]. The experimental process lot variations were based on the standard SiGe-120 process. The pre-radiation SiGe HBTs for the experimental substrate processes displayed only minor differences in terms of general *ac* and *dc* performance, compared to the SiGe HBTs from the standard process. None of these SiGe technologies was intentionally radiation-hardened in any way.

III. Experiment

A SiGe HBT emitter geometry of $0.2 \times 4.52\ \mu m^2$ was used for comparison of the the Jazz SiGe-120 standard process, the experimental processes fabricated with a 1500 Ω-cm Si substrate, and a 2 μm thick SOI on 0.4 μm buried oxide. In addition, a

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TABLE I
CHARACTERISTICS OF JAZZ SIGE-120 SIGE HBT BICMOS TECHNOLOGY.

NPN	f_T (GHz)	150
	f_{max} (GHz)	180
	BV_{CEO} (V)	2.3
CMOS	V_{DD} (V)	1.8
	L_{eff} (μm)	0.18

120 GHz SiGe HBT BiCMOS reference technology (IBM 7HP) [7] and a 200 GHz SiGe HBT reference technology (IBM 8T) [8] were examined. The radiation exposure and testing conditions were the same for all of the SiGe technologies, facilitating unambiguous comparisons.

The samples were irradiated with 63.3 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radiation source (Ta scattering foils) located several meters upstream of the target establish a beam spatial uniformity of about 15% over a 2.0 cm radius circular area. Beam currents from about 20 nA to 100 nA allow testing with proton fluxes from 1.0×10^9 to 1.0×10^{12} proton/cm^{2}sec. The dosimetry system has been previously described [9] [10], and is accurate to about 10%. At proton fluences of 1.0×10^{12} and 5.0×10^{13} p/cm^2, the measured equivalent gamma dose was approximately 135 and 6,759 krad(Si), respectively. The SiGe HBTs were irradiated with all terminals grounded for the *dc* measurements and with all terminals floating for the *ac* measurements. The *ac* samples were then measured, and re-irradiated with a fluence of 5.0×10^{13} p/cm^2, and subsequently remeasured, resulting in a maximum net proton fluence of 1.0×10^{14} p/cm^2. We have previously shown that SiGe HBTs are not sensitive to applied bias during irradiation. Wirebonding of *ac* test structures is not compatible with robust broadband measurements, and hence on-wafer probing of S-parameters was used to characterize the high-frequency performance. The samples were measured at room temperature with an Agilent 4155 Semiconductor Parameter Analyzer (*dc*) and an Agilent 8510C Vector Network Analyzer (*ac*) using the techniques discussed in [11].

IV. *dc* RESULTS

The forward-mode Gummel characteristic for the standard process, shown in Figure 2, demonstrates the slight increase in base current as proton fluence is increased. This type of base current degradation with proton fluence has been previously reported for SiGe HBT's [1]. This excess base leakage is a function of proton-induced G/R centers, generated around the emitter periphery, in the emitter base spacer of the device [12]. As seen in Figure 3, the SOI and HRS substrate variations also demonstrate this phenomenon, as expected, with the SOI technology displaying the least base current degradation.

Based on the *dc* data, it is tempting to conclude that SOI SiGe HBT technology is inherently more total dose tolerant. However, as seen in Figure 2 these devices exhibit a finite amount of base current non-ideality, even in the pre-radiation case (especially in the case of the SOI device). Therefore, it is difficult to definitively claim that one substrate variant is less total dose tolerant than the others, although we are able to observe that the SiGe HBTs fabricated on HRS material appear to be less tolerant than both the standard and SOI processes. Even with this caveat, all of these SiGe technologies demonstrate very respectable post-radiation performance up to a proton fluence of 5.0×10^{13} p/cm^2 (i.e., multi-Mrad radiation levels), without any additional radiation hardening. This is clearly good news.

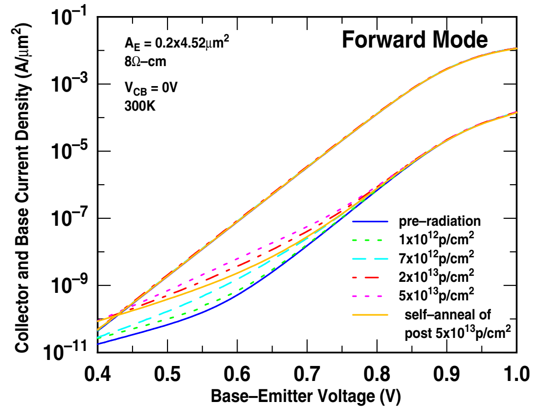

Fig. 2. Forward-mode Gummel characteristics of the SiGe HBT from the standard process.

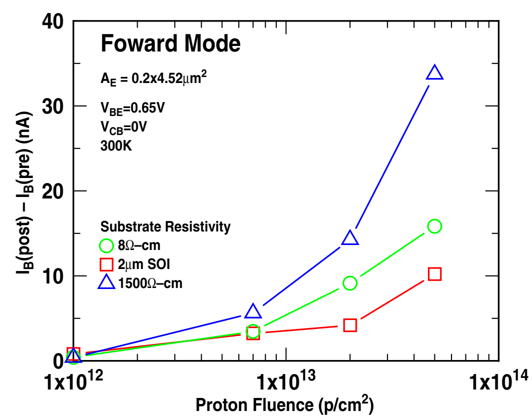

Fig. 3. Comparison of absolute base current variation in forward-mode versus proton fluence for the standard process, the HRS, and the SOI technologies.

The current gain (β) is coupled to the base current leakage. Figure 4 displays the shift in peak β as the fluence is increased for the standard SiGe-120 process. This degradation is only severe at low bias levels (significantly lower than the bias point at which peak f_T occurs, and hence would not adversely affect most circuit applications). Figure 5 displays the β degradation at peak f_T (where critical RF circuits will operate), and is negligible ($<$ 5%) for all substrate splits.

An examination of the inverse-mode Gummel characteristics (i.e., interchanging the emitter and collector terminals), yields insight into radiation-induced damage in the collector-base junction of the device [1]. It is apparent from Figure 6 that the

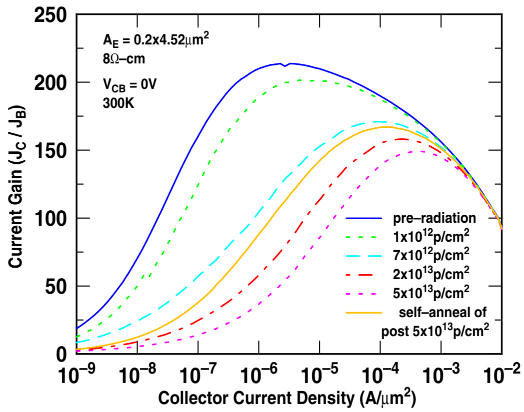

Fig. 4. Current gain on bias current as a function of proton fluence for the standard process SiGe HBT.

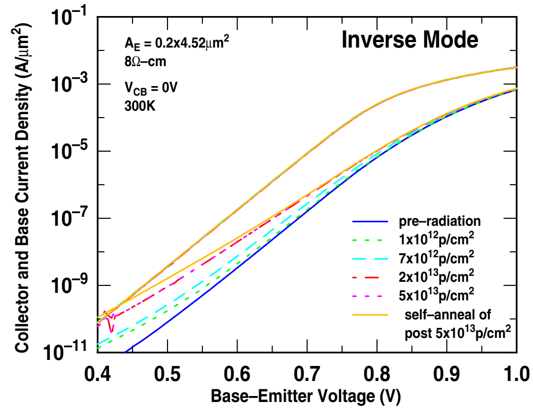

Fig. 6. Inverse-mode Gummel characteristics of standard process SiGe HBT.

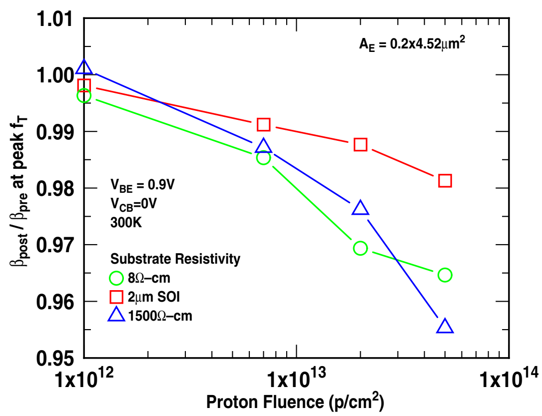

Fig. 5. Normalized current gain characteristics versus proton fluence for standard process, the HRS, and the SOI technologies.

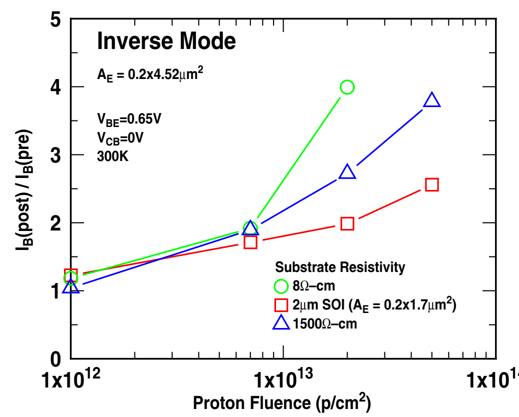

Fig. 7. Comparison of normalized base current in inverse-mode versus proton fluence for the standard process, the HRS, and the SOI technologies.

collector-base junction has experienced minor damage due to proton irradiation. This can be said for all 3 of the substrate variations, however, as seen in Figure 7. It is also interesting to note from Figures 2 and 6 that self-annealing occurs in these devices after irradiation. The annealing of the forward-mode Gummel characteristics suggests the elimination of proton induced G/R traps in the emitter-base spacer region. In contrast, there is minimal recovery in the collector-base junction, presumably due to the differences between the composition of the emitter-base spacer and the shallow trench oxide.

V. *ac* Results

The scattering parameters (S-parameters) of the SiGe HBTs were characterized up to 48 GHz for a wide range of bias currents, while maintaining a constant collector-base voltage. This data was then de-embedded using standard "open-short" structures, and used to calculate Mason's Unilateral Gain (U) and the small signal current gain for a shorted output termination (i.e., h_{21}). Values for f_T and f_{max} were obtained by extrapolating (using a -20 dB/decade slope) from the values measured at 40 GHz. Pre-radiation f_T and f_{max} curves versus collector current density can be seen for all three process variations in Figures 8 and 9, respectively. From these data it is clear that the incorporation of the HRS and SOI substrates resulted in only negligible degradation of SiGe HBT *ac* performance. In addition, as seen in Figure 10, there is negligible degradation in f_T and f_{max} for these devices in any of the process variations for proton fluences up to 1.0×10^{14} p/cm^2 (> 13 Mrad total dose!). This was also the case for the post radiation measurements for r_{bb}. For all three of these performance metrics, the variations observed in post-irradiated data was within ± 5% (which is essentially within the error bars associated with S-parameter measurement and de-embedding). This is, again, clearly excellent news.

VI. Technology Comparisons

As stated above, a 0.2×1.2 um^2 device from a 120 GHz SiGe HBT technology (IBM 7HP) [7] and a 0.12×10 um^2 device from a 20 GHz SiGe HBT technology (IBM 8T) [8], were included in the radiation experiments for comparison purposes to the standard substrate process investigated here. The *dc* and *ac* radiation response for these three SiGe technologies is shown in Table II.

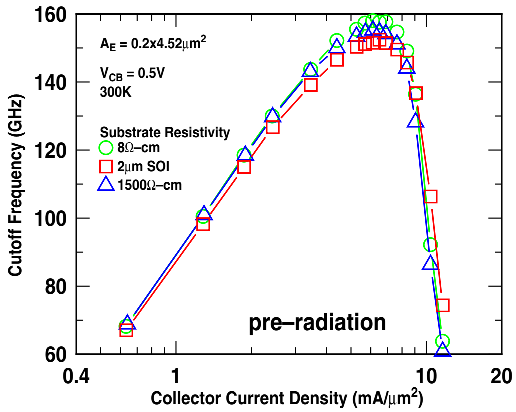

Fig. 8. Pre-radiation comparison of f_T for the standard process, the HRS, and the SOI technologies.

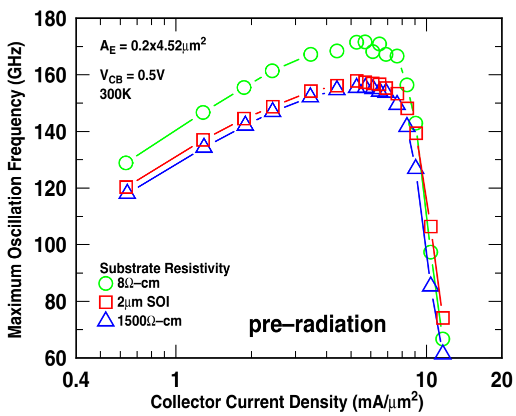

Fig. 9. Pre-radiation comparison of f_{max} for the standard process, the HRS, and the SOI technologies.

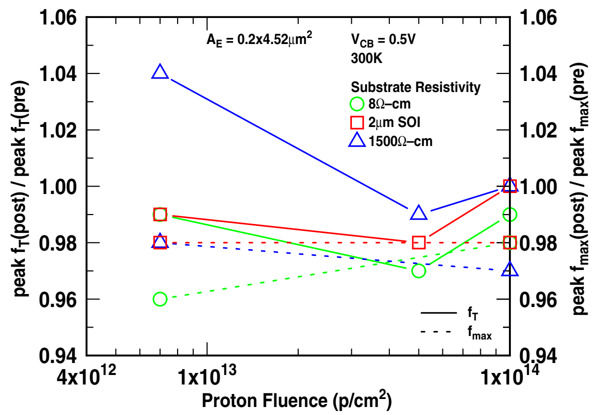

Fig. 10. Normalized f_T and f_{max} versus proton fluence for the standard process, the HRS, and the SOI technologies.

TABLE II

COMPARISON OF PROTON TOLERANCE FOR THE STANDARD PROCESS (PRESENT WORK), A DIFFERENT 120 GHZ HBT SIGE TECHNOLOGY, AND A DIFFERENT 200 GHZ SIGE HBT TECHNOLOGY

Parameters	This Work (8 Ωcm)		SiGe #1 120 GHz [7]		SiGe #2 200 GHz [8]	
Fluence	7E12	5E13	7E12	5E13	7E12	5E13
$I_{B(post)}/I_{B(pre)}$	2.3	6.9	1.9	9.1	2.1	4.2
Inverse Mode $I_{B(post)}/I_{B(pre)}$	1.5	4*	1.3	1.4*	0.9	1.0*
Fluence	7E12	1E14	7E12	1E14	7E12	1E14
f_T (GHz) (V_{CB}=0.5V)	155	156	103	108	201**	206**
f_{max} (GHz) (V_{CB}=0.5V)	160	165	110	101	285**	285**

* Inverse Mode Gummel Data Taken at 2E13 p/cm^2

** f_T and f_{max} measured at V_{CB}=1V

True apples-to-apples comparisons between competing IC technologies are impossible to meaningfully perform due to subtle profile variations, differences in standard device geometries, etc. That said, clearly, all of the three SiGe technologies exhibit excellent tolerance of proton irradiation without additional radiation hardening. This is obviously excellent news for the space community.

VII. SUMMARY

The first investigation of proton tolerance the Jazz SiGe-120 process is reported, and demonstrates comparable performance to previously documented SiGe technology reference points. In addition, the proton tolerance of SiGe HBTs fabricated on both SOI and HRS demonstrates that all three substrate materials yield excellent performance for proton fluences up to 5×10^{13} p/cm^2. These result opens the door to new possibilities involving SiGe HBT technology build on various substrate materials that may be potentially needed for both SEU immunity and high quality transmission lines and passive elements for emerging space communications systems.

VIII. ACKNOWLEDGEMENT

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